

RADIATION FROM JET COMBUSTOR FLAMES

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A B S T R A C T

Radiant energy from aircraft gas turbine type combustion processes was investigated using a laboratory scale combustor in which two paraffinic and two aromatic test fuels were burned at combustor pressures from one to fifteen atmospheres. Infrared flame emission and absorption spectra from 0.5 to 15 microns in wavelength were obtained.

The average transverse emissivity of the infrared spectral region ranged from 0.03 for non-luminous flames to nearly one for luminous flames. Transverse flame emissivity increased with pressure and in general, flame emissivities were higher for the aromatic fuels. Radiant energy transferred to the combustor parts represented as much as ten per cent of the total energy released in luminous flames.

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S U M M A R Y

Characteristics of the energy radiated from aircraft gas turbine type combustion processes were investigated using a laboratory scale combustor. Two paraffinic test fuels, normal heptane and isooctane, and two aromatic test fuels, benzene and toluene, were evaluated. Three different test conditions were selected having operating pressures of 40, 150, and 450 inches of mercury absolute. Infrared flame emission and absorption spectra, from 0.5 to 15 microns in wavelength were obtained at five different locations around the combustor. This was also done without combustion, and without fuel; to obtain fuel, and air, absorption spectra.

The average transverse emissivity of the infrared spectral region for non-luminous flames was approximately 0.03; but it increased, with increasing flame luminosity, to nearly one. The transverse emissivity of the flames increased with increasing combustor pressure. In general, flame emissivities of the aromatic fuels were higher than those of the paraffinic fuels. Energy transferred by radiation to combustor parts was an appreciable portion of the total energy released in luminous flames, varying from less than one per cent to greater than ten per cent.

Total radiation pyrometers must include the 1 to 5 micron spectral region to give reliable indications of the total infrared radiation emitted by jet combustor type flames. For low luminosity flames sapphire optics will give substantially more reliable results than quartz optics. If pyrometric observations are made through long columns of exhaust gases, it may be necessary to take into account the absorption due to the combustion products and smoke.

The emissivity of the carbon dioxide 4 to 5 micron band was nearly one over a large range of operating conditions and fuel type. Indications are that the intensity of radiation in this spectral region should serve as a good index of the flame temperature, since it would be essentially independent of flame luminosity and atmospheric absorption, if a narrow band-pass pyrometer were used.

I. INTRODUCTION

The brilliantly luminous flames observed with all test fuels, whether paraffinic or aromatic, have been among the more prominent effects observed in combustion studies at pressures above ten atmospheres. At such pressures combustor flame tube deposits have dropped to very low levels in the face of increased carbon formation as shown by measurements of density of exhaust gas smoke. However, reduction in deposits at such pressures are accompanied by buckling of combustor liners, distortion of their primary air inlet holes, and loss of metal from their exposed surfaces. These were considered to be manifestations of higher metal temperature resulting from more intense flame radiation.

It was felt, in view of industry trends towards relatively high pressure ratio turbojet powerplants, that a more detailed study of the characteristics of the radiant energy emitted from two-inch diameter jet combustor flames might be both worthwhile and timely. Work by two other investigators (1,2) has also shown increasing pressure to cause more intense heat transfer from the flame zone (primary combustion zone) to the surrounding metal walls, using full scale combustor cans at pressures between one and three atmospheres. In both cases the much higher radiation intensities from yellow or luminous flames (containing glowing particles of free carbon as individual radiating centers) compared to that from blue or non-luminous flames was mentioned. It is, of course, known that the formation of free carbon in flames is favored by high operating pressures. Therefore the work was planned to emphasize realism of the combustion environment, particularly with regards to pressure.

It was decided to establish whether the use of quartz windows to protect total radiation pick-ups from the high combustor pressures and temperatures (as was done for the work of Reference 1) was permissible from the energy transmission standpoint. That is, is there appreciable radiant energy emitted at wavelengths longer than three microns in the infrared region, beyond which quartz fails to transmit appreciably? Work discussed in Reference 3 using atmospheric, bunsen burner type flames suggested that this long wavelength radiation comprised a large part of the total radiant energy emitted. The experimental program which evolved had the objectives of determining detailed radiant energy-versus-wavelength relationships by the use of spectroscopic instrumentation, for fuels spanning a wide range of hydrocarbon type, at combustor operating conditions representative of (1) ramjet, (2) current turbojet and (3) future turbojet powerplants.

II. TEST PROGRAM

Pure hydrocarbon test fuels were used to insure that differences in flame radiation produced by gross differences in hydrocarbon structure would be clearly evident. Table I lists characteristics of the four fuels selected — normal heptane, isooctane, benzene and toluene. These relatively non-viscous volatile fuels were chosen to minimize, or at least render constant, the effects of liquid atomization and vaporization on carbon formation and, hence, flame radiation.

The schedule of operating conditions chosen for this work is shown by Table II. Test condition 40 is a combination of low absolute pressure and high inlet air velocity representative to some extent of ramjet type combustion systems. It was selected as a "base" condition at which all four fuels were expected to burn with blue, smokeless flames. It therefore served to show whether differences might exist between fuels in radiant energy solely of the molecular, or non-luminous, type.

Test condition 150 was chosen to simulate the type of combustion environment provided by turbojet engines of relatively low pressure ratio at sea level conditions, or by engines of higher pressure ratio at high altitudes. Past observations have shown flames produced under conditions such as this from the two aromatic test fuels to be entirely luminous in appearance, while the two paraffinic test fuels produced semi-luminous flames having both blue and yellow regions.

Test condition 450 simulated the type of conditions encountered with high pressure ratio turbojets, particularly at low altitude conditions. Pressure was the only variable changed here from condition 150, since a corresponding increase in inlet air temperature (desirable for strict realism) was decided against because of doubts concerning the ability of the potassium bromide windows, through which the flame radiation measurements were taken, to withstand temperatures much above 400 F. Inlet velocity, too, was constant for both conditions 150 and 450. A velocity of 100 ft/sec was chosen as a reasonably valid compromise between conditions in older, low pressure ratio engines (60 - 80 ft/sec) and in newer, high pressure ratio units (125 - 180 ft/sec).

Fuel-air ratio was maintained constant at the intermediate level of 0.010 for all three test conditions, facilitating interpretation of the radiation data for conditions 150 and 450 on the basis of pressure alone.

III. EXPERIMENTAL SET-UP

A. Combustor Details

The combustor test facility was built around a compressor plant capable of supplying air at mass flow rates up to 2.5 lbs/sec and pressures from 4 to 500 in. Hg abs to a battery of electric resistance heaters, with which combustor inlet temperatures up to 1000 F could be attained. From these the air passed to the combustor inlet piping shown in Figure 1, which also gives the location of the test combustor itself and the stations at which the flame radiation measurements were made. Fuel was introduced into the combustor by pressure atomization through a conventional swirl type nozzle, while air for combustion and cooling entered through holes in the flame tube and nozzle holder. These flame tubes were made from heavy walled (Schedule 40) stainless steel (Type 304) 2-inch pipe to resist distortion and warping in the presence of extreme variation in operating conditions.

A sketch of the flame tube in the combustor test section is shown in Figure 2. The transverse spectroscopic observations on the flames were made through 1/4-inch air inlet holes located diametrically across the tube. The stations numbered 1, 2, and 3 indicate the locations used along the axis of the flame tube. These numbers will be used throughout this report to designate these observation stations. Transverse observations were also made downstream from the flame quench holes in the combustor exhaust gas stream at the station numbered 4.

Axial observations from the exhaust end were made through an observation window in the exhaust elbow approximately 45 inches downstream from the flame tube. This station is designated as station 5. An unobstructed axial view of the flame was obtained from this station.

B. Spectrophotometer Details

A Perkin-Elmer 12C spectrophotometer which provided a convenient means for obtaining both the emission and absorption spectra of the flames was used. The spectrometer was mounted on the laboratory scale jet combustor to form the jet-combustor-spectrophotometer. In the interest of safety and convenience the spectrophotometer was operated by means of controls located outside the test-cell.

The equipment located inside the test-cell was connected with the control, amplifying, and recording system located outside the test-cell by a 25 foot cable.

A schematic diagram of the jet-combustor spectrophotometer is shown in Figure 3. The two-inch diameter flame tube within the combustor test section had 1/4-inch diameter air inlet holes through which the spectra were obtained. To obtain absorption spectra a first image of the Globar source was projected by mirror M1 and lens L1 (aperture 3/4-inch) at the center of the combustor. An image of this first image was projected by lens L2 (aperture 1/2-inch) onto the slit of the monochromator. The radiation from the Globar was modulated at 13 cps by the light chopper C1 with chopper C2 set in the open position. This modulated radiation was dispersed by the monochromator and detected by the thermocouple receiver. The 13 cycle output from the thermocouple was selectively amplified. This amplified signal was synchronously rectified by breaker points attached to the shaft of the chopper C1. The resulting d-c signal, proportional to the amount of radiation falling on the thermocouple, was recorded. Radiation arising between the chopper C1 and the thermocouple receiver was rejected unless it happened to be modulated at 13 cps and had the proper phase. The modulated radiation reaching the thermocouple was derived from the Globar source and passed through the flame in the combustor permitting absorption measurements to be made. Spectra were obtained by continuously varying the wavelength passed by the monochromator over the spectral region desired.

Emission spectra were obtained by setting C1 in the closed position and modulating the radiation leaving the combustion chamber by means of chopper C2. The amplified signal from the detector was synchronously rectified by breaker points attached to the shaft of C2. In this case, only radiation originating between C1 and C2, in the flame tube, was modulated and was thus recorded. With this arrangement the emission or absorption spectra could be obtained by activating the proper chopper and breaker points.

The lenses L1 and L2 of potassium bromide with a focal length of 5.33 inches were separated from the combustion chamber by plates of potassium bromide one centimeter thick. The plates were sealed by means of plastic O-rings to fittings attached to the combustion chamber. Dry air was injected between the window and the combustion chamber as shown in the diagram to cool the potassium bromide plates and to prevent deposition of water, oil, carbon, etc., on the windows.

IV. INFRARED SPECTRAL MEASUREMENTS

Emission and absorption spectra were obtained at stations 1, 2, 3, and 4, but only the emission spectra were obtainable at 5. The four fuels described in Table I were investigated for each of these observation stations along the combustor under the three conditions specified in Table II.

A. Emission Spectra

The short wavelength spectral region, 0.5 to 5.5 microns, was scanned with a constant monochromator slit width (0.100 millimeters). To expedite taking of data and maintain reasonable recorder deflections for non-luminous flames a portion of the long wavelength spectrum, 4 to 12.5 microns, was scanned with a constantly increasing monochromator slit width which varied linearly from 0.22 millimeter at 4 microns to 2.0 millimeters at 12.5 microns. The slit width was held constant at 2.0 millimeters from 12.5 to 15 microns. The slit was continuously opened according to the prescribed schedule by using synchronous motors for driving the monochromator wavelength scanning mechanism and for opening the monochromator slits.

Figures 4 through 7 are short wavelength emission spectra of normal heptane, isooctane, benzene, and toluene flames, respectively. The combustor operating conditions, 40, 150, and 450, are indicated on the spectra. These spectra were obtained at the observation stations 1, 2, 3, and 5 reading from left to right as labeled at the top of the figures. The emission spectra obtained at the post combustion location, station 4, are shown separately in Figure 8 because of their relatively low intensity.

No evidence of abnormal radiation patterns, other than extensions of the black body type of radiation, were noted in the visible region down to 0.5 microns or in the infrared region beyond 5 microns. Therefore, detailed spectra are presented only for the near infrared region from 0.9 to 6 microns.

The variation in the 4.4 micron peak intensities for the spectra at stations 1, 2, and 3 under conditions 150 and 450 and at station 5 under condition 150 is probably a good measure of the reproducibility of the alignment and other instrumental factors. Variations in flame characteristics will account for some other variations.

B. Absorption Spectra

The flame absorption spectra are shown in Figure 9. These spectra were obtained by comparing the Globar energy curve with a fire in the combustor to the energy with no fire in the combustor. The spectra for stations 1, 2, 3, and 4 are arranged from left to right. The spectra from top to bottom are for normal heptane, isooctane, benzene and toluene. The spectra for test conditions 40, 150, and 450 are indicated on the individual curves.

The absorption on the short wavelength side of the 4.4 micron carbon dioxide absorption band was somewhat indeterminate because of the strong carbon dioxide atmospheric absorption. Likewise the absorption in the 2.6 micron region was influenced by changes in the water and carbon dioxide absorption in the optical path outside the flame.

The details of the condition 450 spectra where the average per cent transmission was low, below 30 per cent, were rather meaningless since in some cases the signal to noise ratio was less than one. The "noisiness" (fluctuations of radiation intensity and transmission properties) of the flames appeared to increase with the average absorptivity and luminosity. In general, the energy transmitted by the condition 40 flame was quite steady, noise level of the order of one per cent, condition 150 flame, 5 per cent, the condition 450 flame up to 100 per cent. In the case of emission the noise was never larger than a few per cent of the signal. These noise effects are presumably tied up with the turbulence and density of incandescent material in the flame. Flames having a high spectroscopic noise level were visually "noisy" with considerable fluctuation in the visual intensity, particularly at stations 1 and 2.

Figure 10 shows the absorption spectra of the four vaporized fuels at a pressure of 450 inches of mercury in the combustor, as observed at station 2. The raw fuel was injected into the combustor in exactly the same manner as it was in the flame studies except there was no flame. The fuel and air flow rates were those used for test condition 450. The inlet air temperature was dropped to 350 F. There are some doubts about the validity of these spectra in the 2.6 to 3 micron regions because they were obtained before the deposition of foreign matter, particularly water, on the potassium bromide windows was eliminated.

Figure 11 shows the absorption spectra of the water and carbon dioxide in the complete optical system, combustor included, with 40 and 450 inches of mercury air pressure in the combustor. These spectra were obtained by comparing a smooth Globar emission curve, simulating low water or carbon dioxide absorption, to the experimental curve. The smoothing was done in those spectral regions in which an increase in combustor pressure gave a significant decrease in transmission, namely, at 1.9, 2.6, and 4.3 microns. It will be noted from these curves that the approximately 20 inches between the potassium bromide plates contained a large part of the effective atmospheric absorbing materials at 450 inches of mercury pressure (15 atmospheres).

V. DISCUSSION

A. Infrared Spectra

Inspection of Figures 4 through 7 indicates that the experimental flames may be classified into two groups. In one group molecular (band) type radiation predominates and in the other group black body (continuous) type of radiation predominates. Such a grouping agrees with the visual flame characteristics and the designations non-luminous and luminous, respectively. The table below summarizes this information for the fuels and operating conditions used in this work.

Test Fuel	Test Condition		
	40	150	450
Normal Heptane	non-luminous	non-luminous	luminous
Isooctane	"	"	"
Benzene	"	luminous	"
Toluene	"	"	"

In the non-luminous flame spectra, the molecular bands centered at 1.4, 1.9, and 2.9 microns are water vibrational emission bands. There may be some contribution from carbon dioxide at 2.9 microns. The band in the 4 to 5 micron region was due to carbon dioxide vibrational emission. The shape of these vibrational emission bands was influenced to a large degree by the absorption due to water and carbon dioxide and the air path in the optical train. The absorption at 1.4 and 1.9 microns was due to water; at 2.6 to water and carbon dioxide, and at 4.3 to carbon dioxide. These absorption bands were particularly evident in the station 5 spectra since the radiation traverses about 45 inches of exhaust gases and air at the same pressure as the combustor.

One characteristic of a molecular flame emission band is that the wavelength distribution does not correspond to that of the atmospheric absorption. A large part of the emitted radiation appears at longer wavelengths than the atmospheric absorption bands. This may be explained by the fact that the emitting gas is at a higher temperature than the atmospheric absorbing gas. At elevated temperatures the population of the energy states of the molecules is different from that at lower temperatures. The wavelengths of the emission or absorption resulting from transitions between the higher energy states will not coincide exactly with the transitions between the two lowest states. This situation arises because, in general, the molecule is an anharmonic oscillator rather than a harmonic one. The correspondence between the molecular flame emission wavelength distribution and the flame absorption distribution can be seen by inspection of figures 4 through 9. Since the anharmonicity should increase at higher energy

states the flame absorption and emission bands should broaden toward longer wavelengths as the flame temperature is increased. This effect is also evident if the atmospheric absorption of carbon dioxide at 4.3 microns in the station 1, 2, and 3 emission spectra is compared with the hot exhaust gas absorption in the station 5 emission spectra. Also a comparison of the flame absorption spectra at stations 1, 2, and 3 with the cooler station 4 absorption and the atmospheric absorption shows the same type broadening of the absorption band with temperature.

The spectra of the non-luminous flames show a small background of continuous radiation while in the luminous flame spectra the continuous radiation obscures molecular radiation. In the cases of intermediate luminosity molecular radiation peaks are superimposed on the continuous background. The absorption curves show that in the regions of strong molecular emission the absorptivity is higher than the background. As the luminosity of the flame increases, as evidenced by the increased intensity of the continuous radiation, the molecular bands become less pronounced. It will be noted that, for those flames where the average absorption is nearly complete the continuous radiation at 4.4 microns is no more intense than the molecular radiation under less luminous conditions. Therefore, for the central portion of this band the emissivity is essentially one in the two-inch diameter combustor at pressures above 150 inches of mercury. That is, the radiation intensity at this wavelength is equal to that of a black body operating at the temperature of the flame.

B. Black-Body Considerations

In order to study the relationship between the continuous flame radiation in luminous flames and black body radiation the Globar emission was compared with a theoretical black body operating at the same temperature as the Globar. Figure 12 is a comparison of the short wavelength experimental Globar radiation curve with a theoretical 1600 K Globar. The agreement between the experimental and theoretical Globar curves is sufficiently close to warrant the comparison between the continuous flame emission and theoretical black body radiation curves.

Figure 13 shows the relationship between the station 5, condition 450, Figure 7, toluene flame emission and the theoretical black body radiation curves for 1800 K. Except for the spectral regions where the exhaust gas and atmospheric absorptions are evident the toluene flame emission curve agrees quite well with the 1800 K theoretical curve. This indicates that at wavelengths shorter than 6 microns the continuous radiation is very nearly black body in character.

The deviation between the theoretical 1800 K and the station 5 toluene flame emission spectrum at wavelengths shorter than about one micron is probably due in part to smoke absorption. There appears to be little change in the intensities at wavelengths greater than one micron with large changes in exhaust smoke concentration although the visible radiation was almost completely obliterated in some cases at station 5 by the 28 inch column of smoke. Also under conditions of high emissivity the intensity of the radiation at stations 1 and 2, with no smoke between the flame and observer, is comparable with the station 5 intensity. This indicates that the smoke as such in the exhaust had little influence on the amount of infrared radiation from the toluene flame reaching an observer at station 5.

However, examination of the benzene spectra in Figure 6, station 5, shows greater infrared radiation absorption by the smoke. In this case the condition 150 spectrum at wavelengths greater than 2.5 microns has about the same shape as the condition 450 spectrum, but the latter curve falls below the condition 150 curve at wavelengths less than 2.5 microns. This reduction in radiation intensity because of smoke increases as the wavelength decreases. The greater reduction in radiation intensity over a broader wavelength band in the case of benzene probably is associated with the amount and a larger particle size of the incandescent material present in the flame.

C. Flame Temperature

The shape and peak wavelength of the continuous radiation for the luminous flames, as well as the intensity in the four to five micron region for all flames at conditions 150 and 450, indicates that the temperatures are nearly the same for all the flames. Further, the luminous material in the flame appears to be at the same temperature as the carbon dioxide gas in the flame.

It has been pointed out (4,5), that the intensity of the 4.4 micron carbon dioxide emission would be a good measure of the flame temperatures. In the case of the jet combustor it appears that the residence time within the primary combustion zone is sufficient to establish an apparent thermal equilibrium between the incandescent particles and the gas molecules. Within the primary combustion zone of the turbulent flames observed here probably in excess of 10^6 collisions occur per molecule. With a reasonable degree of interaction, on collision, between translation and vibrational excitation some degree of equilibrium between translational and vibrational temperatures may be expected.

Since the emissivity of the carbon dioxide radiation is essentially one for the two inch combustor at pressures above 150 inches of mercury and would approach one at lower pressures in larger scale combustors, the intensity of the carbon dioxide 4.4 micron radiation should serve as a good radiation thermometer. It would be unaffected by the luminosity of the flame and the temperature of the combustor walls seen through the flame. By making the measurement at a wavelength slightly longer than the atmospheric absorption band the measurement would be independent of the external optical path lengths. Since the emission band broadens toward longer wavelengths with increase in temperature and the intensity increases as a power greater than one with the temperature, the relative accuracy of such a pyrometer should increase with increased temperature. Since the incandescent particles appear to be in thermal equilibrium with the gas it would be reasonable to expect the carbon dioxide molecules to be nearly in thermal equilibrium with other gases in the flame.

Figure 14 shows the theoretical relationship between the intensity of the 4.4 micron emission (emissivity of one) and temperature.

D. Total Radiation Measurement

At a temperature of 1800 K about 90 per cent of the radiation emitted by a black body will be emitted at wavelengths shorter than five microns. This percentage drops to about 85 per cent at 1600 K and rises to more than 95 per cent at 2500 K. Therefore, in studying the total radiant energy from luminous flames the uncertainty induced by ignoring radiation of wavelengths greater than about five microns will not seriously prejudice our results. In the discussions that follow all energy integrations are over the range 0.87 to 5.8 microns.

A source of error is the contribution of energy by the flame tube which is measured as flame radiation. In Figure 13 the 700 K curve shows the scale of the contribution to be expected from the flame tube if the area of the flame tube observed by the spectrophotometer is the same as the area of the flame observed. In the case of non-luminous flames this may become a sizable portion of the total radiation at wavelengths shorter than 5.8 microns.

Considering the non-luminous flame spectra, condition 40, in Figures 4 through 7 the continuous radiation present may be approximately synthesized from the 700 K and 1800 K curves of Figure 13. Figure 15 is a plot of the per cent of radiation in the 0.8 to 5.8 micron region due to molecular radiation of carbon dioxide and water together with the continuous radiation due to the flame tube walls (700 K) and the incandescent material in the flame (1800 K) versus observation station along the flame tube for the four fuels. The curves are labeled as

to the sources of the radiation (CO_2 , H_2O , Fe, and C). Fe and C represent the contributions due to the flame tube and the incandescent material, respectively.

Figure 16 shows the variation of radiation intensity with position along the axis of the combustor for individual fuels at the three test pressures. The data are for observation stations 1, 2, 3, and 4.

Figure 17 shows the variation of radiation intensity with fuel type at test conditions 40, 150, and 450 for observation stations 1, 2, 3, and 5. It should be noted that the total radiation intensity at station 5 decreased for the two aromatic fuels when the combustor pressure was raised from 150 to 450 inches of mercury. This effect was most pronounced for benzene. This probably can be attributed to the smoke in the exhaust gases between the flame and station 5.

The information in Figure 18 is of a more speculative nature. It was assumed that the density and character of the flame would not be changed in going to larger more practical sized combustors. The scaling factors used were 3X for diameter and 2X for length of the primary combustion zone. Figure 18 then shows for a hypothetical six-inch combustor the radiation intensity variation with fuel type at comparable operating conditions for various positions around the flame corresponding to stations 1, 2, 3, and 5 in the laboratory scale combustor. The station 5 situation indicates the radiation intensity to which a turbojet engine turbine nozzle might be exposed. These data were further simplified by assuming that the paraffinic fuels, normal heptane and isooctane, were nearly alike and that the two aromatic fuels, benzene and toluene, were nearly alike.

These extrapolations indicate that at low pressure and high velocity, test condition 40, there appears to be little significant variation with fuel type. At intermediate pressure with reduced velocity, test condition 150, there were significant differences in the radiant energy emitted by paraffinic and aromatic flames as seen from stations 1, 2, and 5 (nozzle). At high pressure with velocity the same, test condition 450, there appears to be less change in radiation intensity with fuel type. At station 3 the differences between the two fuel types were not large for any operating condition.

In making instrumental measurements of total radiant energy by means of a total radiation pyrometer using a black detector the transmission characteristics of a combustor window material are important. If the radiation is limited to wavelengths less than 2.5 microns by the use of Pyrex or Vycor window material, then the amount of radiation measured may give little indication of the amount of radiation present. The transmission spectrum of a typical Vycor combustor window is shown in Figure 19. For 1800 K flame the ratio of the amount of radiation measured to the total will vary from a few per cent (about 2) to about 60 per cent depending upon the luminosity of the flame. The emissivity of the continuous radiation in a two-inch burner varies over wide limits from 0.01 to essentially one. In the non-luminous flame only a small percentage of the molecular radiation for small scale flames lies at wavelengths less than 2.5 microns.

As pointed out previously about 90 per cent of the continuous radiation from an 1800 K black body is at wavelengths shorter than 5.5 microns. Probably 75 per cent of the molecular radiation from the two-inch combustor has wavelengths shorter than this 5.5 microns. Thus, based on the combustor spectral data shown here, if observations of flame radiation are made through sapphire windows the data should give fairly reliable indications of the total amount of radiation present. However, if the observations are to be made through long columns of exhaust gases the absorption of the smoke must be taken into account. The transmission spectrum of typical sapphire and quartz combustor windows are shown in Figure 19.

There would be some advantage to extending the limiting wavelengths to ten microns by using calcium fluoride windows. This would include about 98 per cent of the 1800 K continuous radiation. A corresponding larger proportion of the molecular radiation would be included. However, the gain in the larger fraction of energy obtained would probably not offset the advantages of using the more rugged sapphire rather than the soft and somewhat fragile calcium fluoride.

E. Combustion Process

In the infrared absorption spectra of the experimental flames, Figure 9, the absorption due to carbon-hydrogen stretching vibration at 3.4 microns appears irregularly and is not strong compared to the raw fuel absorption in Figure 10. The 3.4 micron absorption is recognized only at test conditions 40 and 150. Further, it appears most frequently at stations 1 and 2. This suggests that upon entering the combustion zone the hydrogen is immediately stripped from the carbon chains by molecular collision or radiation absorption (vibrational excitation).

A comparison of the radiation spectra of the experimental flames and the absorption spectra of the fuels indicates that the radiative transfer of energy from the flame to the fuel is a somewhat inefficient process. This is particularly evident in non-luminous flames where the molecular radiation bands of the flame do not coincide with the absorption bands of the fuel. In the luminous situation the fuel absorbs over spectral regions containing about 10 per cent of the available energy. This is the result of the high intensity of the continuous radiation in the 3.4 micron region.

VI. CONCLUSIONS

The following are short restatements of what are believed to be the significant findings of this work. They are relative to the laboratory scale jet combustor used, under the particular experimental conditions of this study.

(1) Non-luminous flames were characterized by discontinuous radiation, i.e., band emission of molecular origin. The emissivity in these molecular bands approached one only in the carbon dioxide, 4 to 5 micron, band. The average transverse emissivity, of the infrared spectral region from 1 to 15 microns in wavelength, was approximately 0.03.

(2) Luminous flames were characterized by a predominance of continuous radiation, which was black body in nature. For intermediate values of luminosity the discontinuous molecular radiation was evident, superimposed on the continuous black body radiation. The transverse emissivity of the continuous radiation varied from a few hundredths to nearly one, depending upon experimental conditions.

(3) In general, the emissivity of both the non-luminous and luminous flames increased with combustor pressure.

(4) The emissivity of the flames varied with fuel type when burned under constant combustor operating conditions. In general, the emissivities of the two aromatic fuels, benzene and toluene, appeared to be higher than those of the two paraffinic fuels, normal heptane and isooctane. This difference decreased at the highest combustor operating pressure, 450 in. Hg abs.

(5) In luminous flames, the heat transferred by radiation to combustor flame tubes, etc., was an appreciable portion of the total energy released. The radiative power varied from less than one per cent to greater than ten per cent of the total energy released, depending upon fuel type and operating conditions.

(6) Flame "noisiness" (fluctuations of radiation intensity and transmission properties) was a direct function of the carbon forming tendency of the flame.

(7) The temperature of the flames studied here (fuel-air ratio 0.01) remained essentially constant over a large range of combustor operating conditions and fuel types. The temperature was in the neighborhood of 1800 K (2800 F) for the particular conditions of this study.

(8) The emissivity of the carbon dioxide 4 to 5 micron molecular emission was nearly one over a large range of operating conditions and fuel types. This indicates that the intensity of radiation in this spectral region is a good indication of the flame temperature and is essentially independent of the luminosity of the flame.

(9) The temperatures of the luminous material in the flame and the carbon dioxide gas appear to be very nearly the same.

(10) Narrow band-pass pyrometers adjusted for, say, the 4.4 micron region should serve as good flame thermometers if the flame cross section is sufficiently large (i.e., at least two inches thick).

(11) The molecular emission and absorption bands will broaden toward long wavelengths with increase in gas temperatures, making narrow band-pass pyrometry independent of atmospheric absorption. In addition, as a consequence of more material being present, the intensity of emission (i.e., emissivity) and absorption will increase with pressure at these longer wavelengths.

(12) Total radiation pyrometers must include the 1 to 5 micron spectral region to give reliable indications of the total infrared radiation emitted by the flame. Window material for such pyrometry is important. Sapphire windows will give substantially more reliable results than quartz without large luminosity and smoke corrections.

(13) Little hydrocarbon as such was present in the flame zone.

(14) Radiative energy transfer from the flame zone to the hydrocarbon fuel was relatively inefficient due to the non-coincidence of the absorption spectra of the fuel and the emission spectra of the flame. This was more pronounced in the case of non-luminous flames than in luminous flames.

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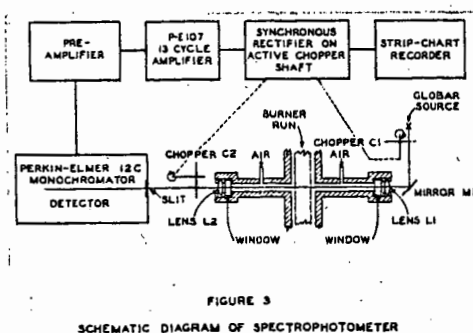
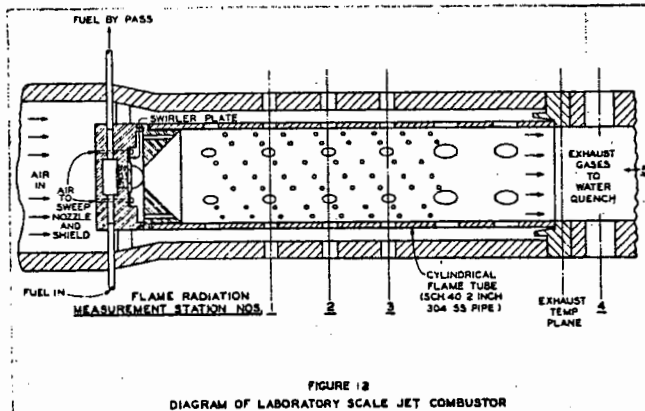
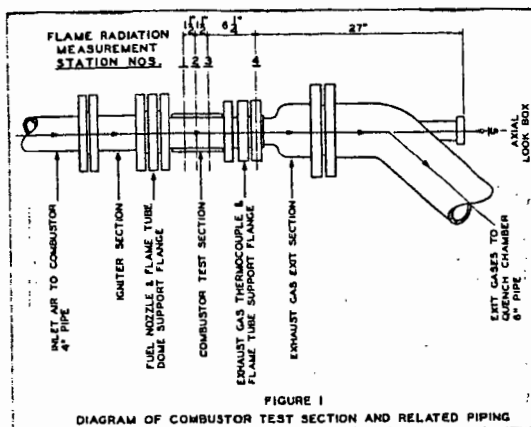
TABLE I
CHARACTERISTICS OF TEST FUELS
 (Technical Grade Products)

	<u>Normal Heptane</u>	<u>Isooctane</u>	<u>Benzene</u>	<u>Toluene</u>
Specific Gravity, 60/60F	0.689	0.692	0.884	0.872
ASTM Distillation, F				
Initial Boiling Point	203	205	176	230
50 Per Cent Evaporated	206	207	176	231
Dry Point	209	208	177	232
Low Heating Value, Btu/lb	19,175	19,065	17,259	17,425
Reid Vapor Pressure, lbs/sq in	1.62	1.71	3.22	1.03
Latent Heat of Vaporization, Btu/lb	156.8	132.2	186.3	177.3
Surface Tension, 80 F, Dynes/cm	17.7	18.9	26.8	25.9
Kinematic Viscosity, 100 F, cs	0.53	0.63	0.60	0.58

TABLE II

SCHEDULE OF OPERATING CONDITIONS

<u>Test Condition</u>	<u>40</u>	<u>150</u>	<u>450</u>
<u>Combustion System</u> <u>Environment Simulated</u>	<u>Ramjet</u>	<u>Turbojet, Low</u> <u>Pressure Ratio</u>	<u>Turbojet, High</u> <u>Pressure Ratio</u>
Combustor Pressure, in. Hg abs	40	150	450
Combustor Inlet Air Temperature, F	300	400	400
Combustor Inlet Air Velocity, ft/sec	350	100	100
Fuel-Air Ratio, lbs Fuel/lb Air	0.010	0.010	0.010



NOTE: FLAME SPECTRA LABELED ACCORDING TO COMBUSTOR PRESSURE (IN. HG ABS.).

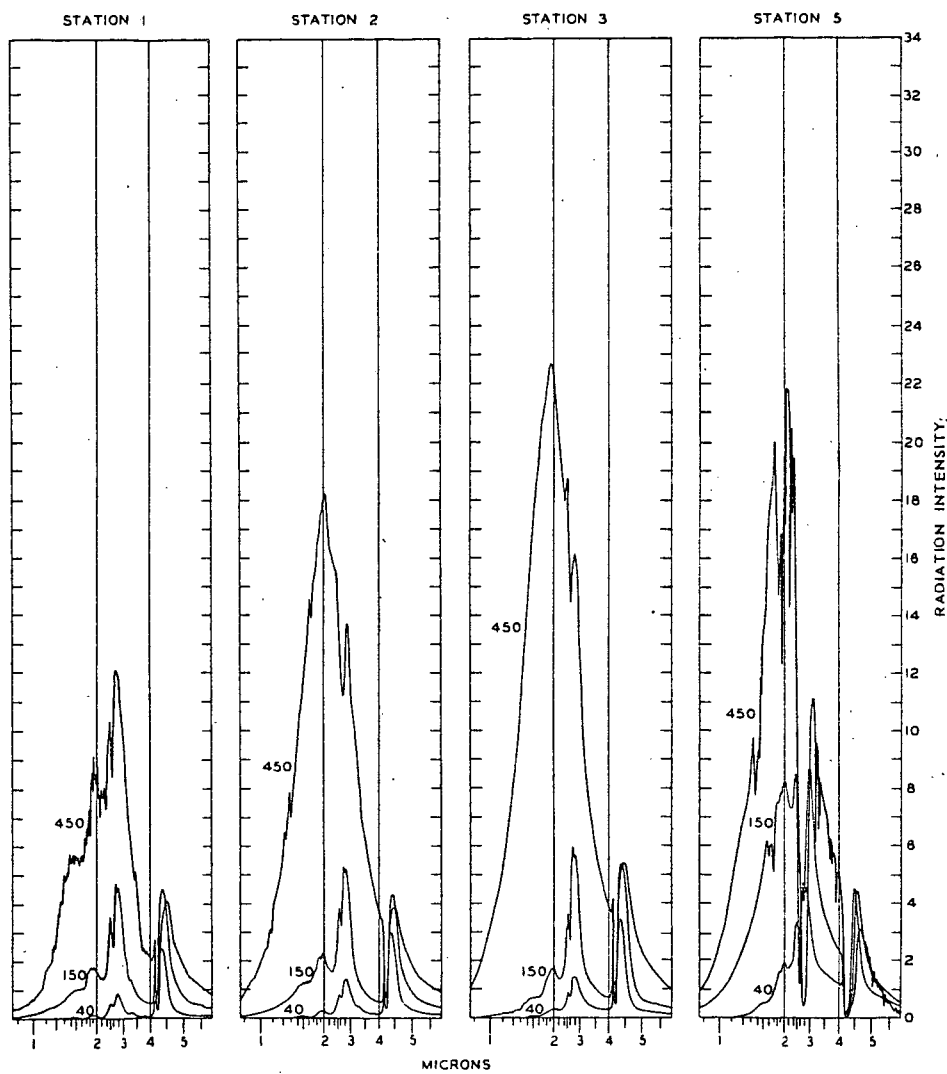


FIGURE 4
NORMAL HEPTANE FLAME EMISSION SPECTRA

NOTE: FLAME SPECTRA LABELED ACCORDING TO COMBUSTOR PRESSURE (IN. HG ABS.)

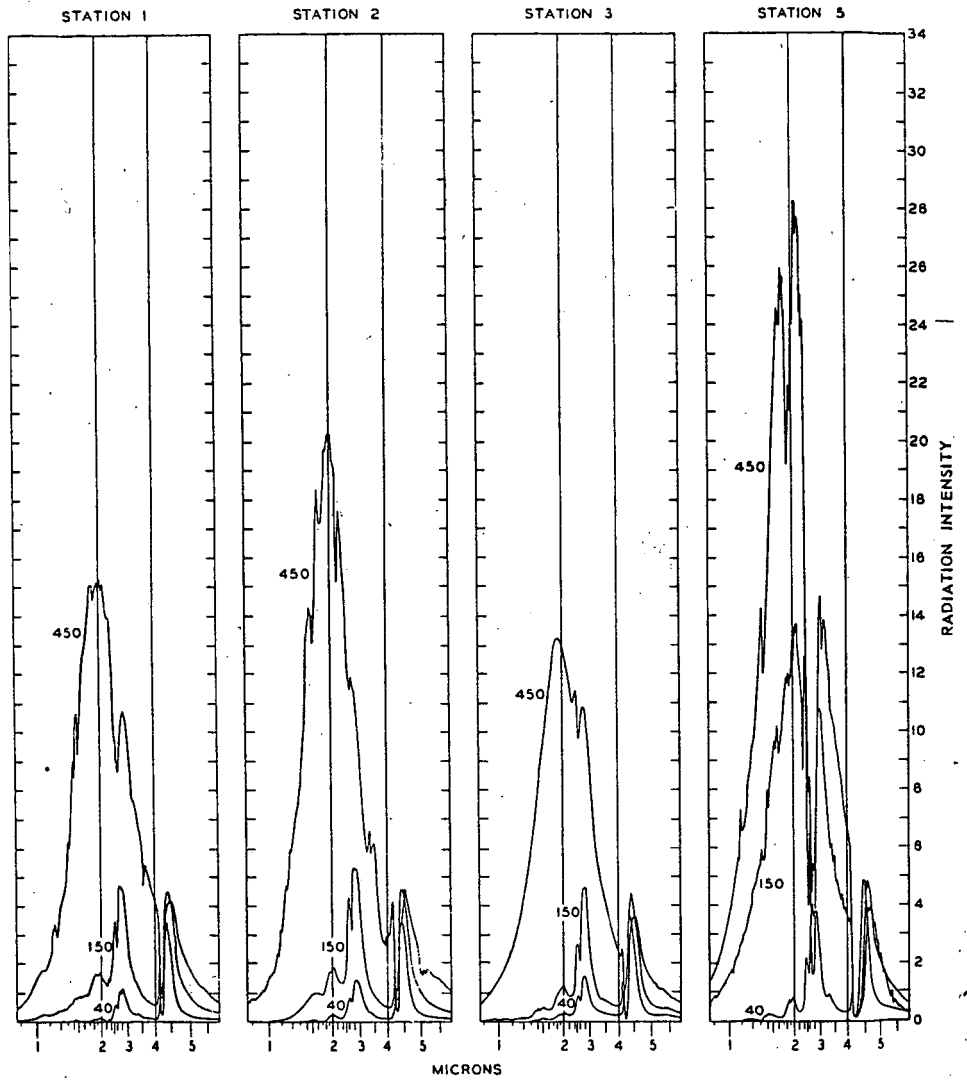


FIGURE 5
ISOOCTANE FLAME EMISSION SPECTRA

NOTE: FLAME SPECTRA LABELED ACCORDING TO COMBUSTOR PRESSURE (IN. HG ABS.)

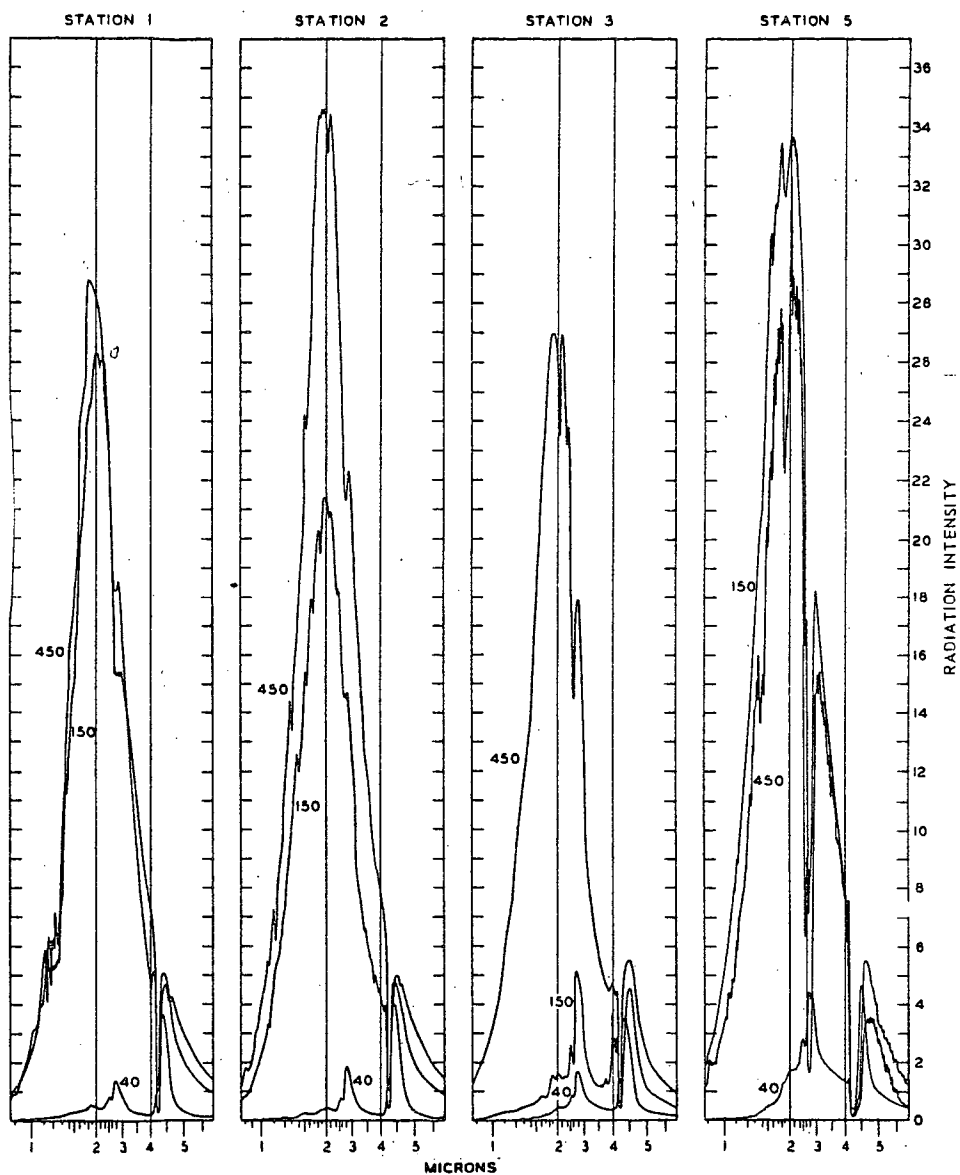


FIGURE 6
BENZENE FLAME EMISSION SPECTRA

NOTE: FLAME SPECTRA LABELED ACCORDING TO COMBUSTOR PRESSURE (IN. HG AES.)

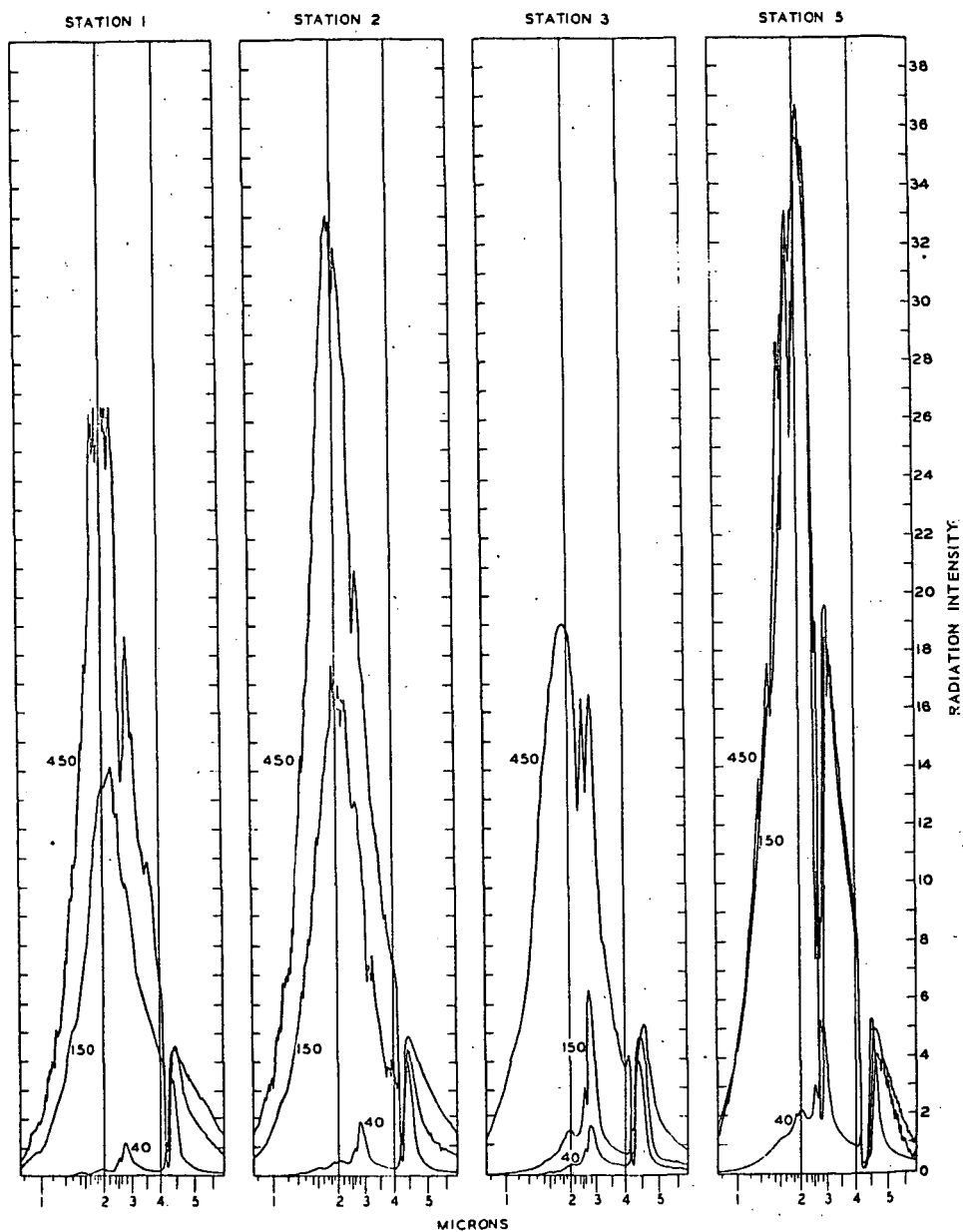


FIGURE 7
TOLUENE FLAME EMISSION SPECTRA

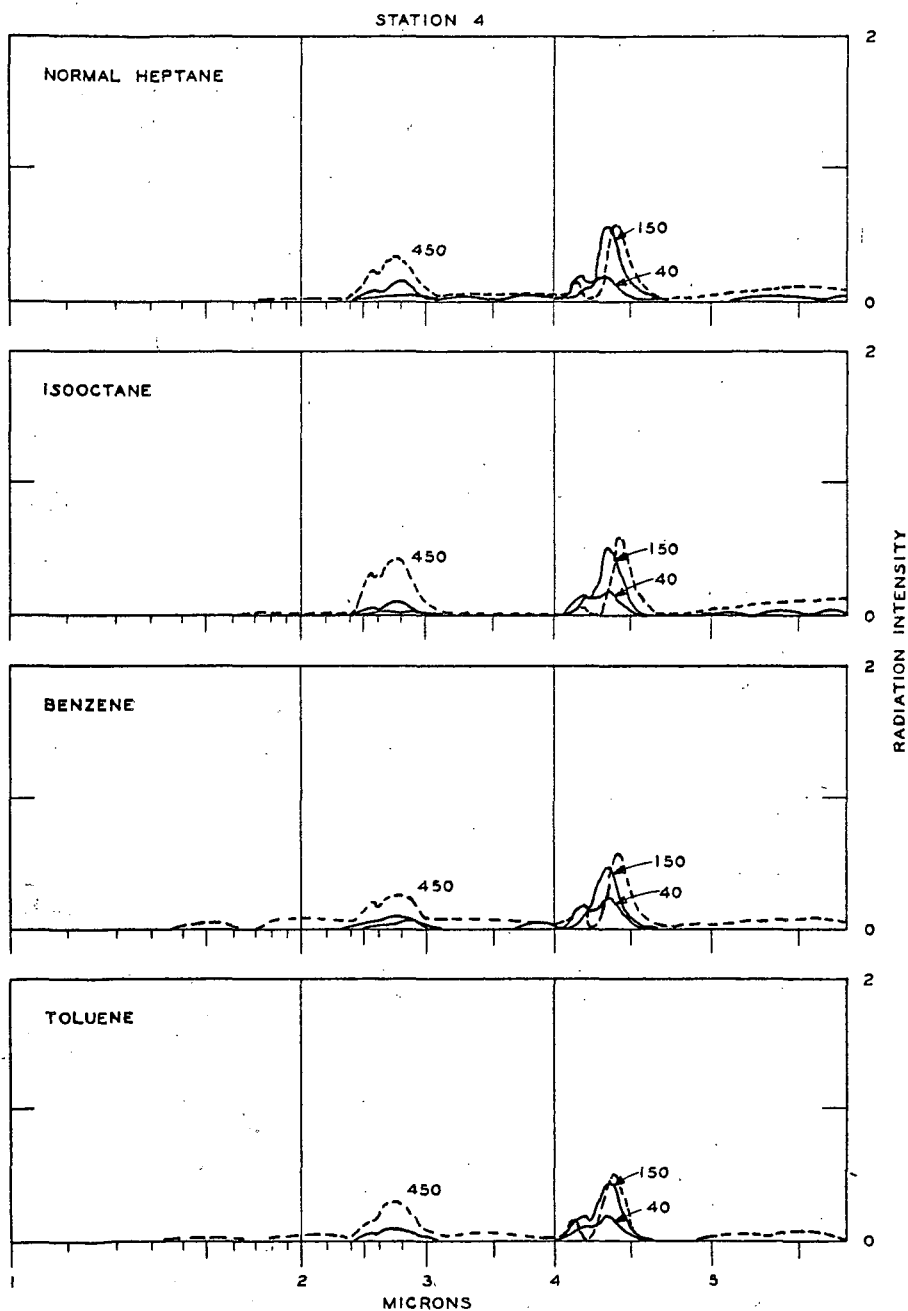


FIGURE 8
EXHAUST GAS EMISSION SPECTRA

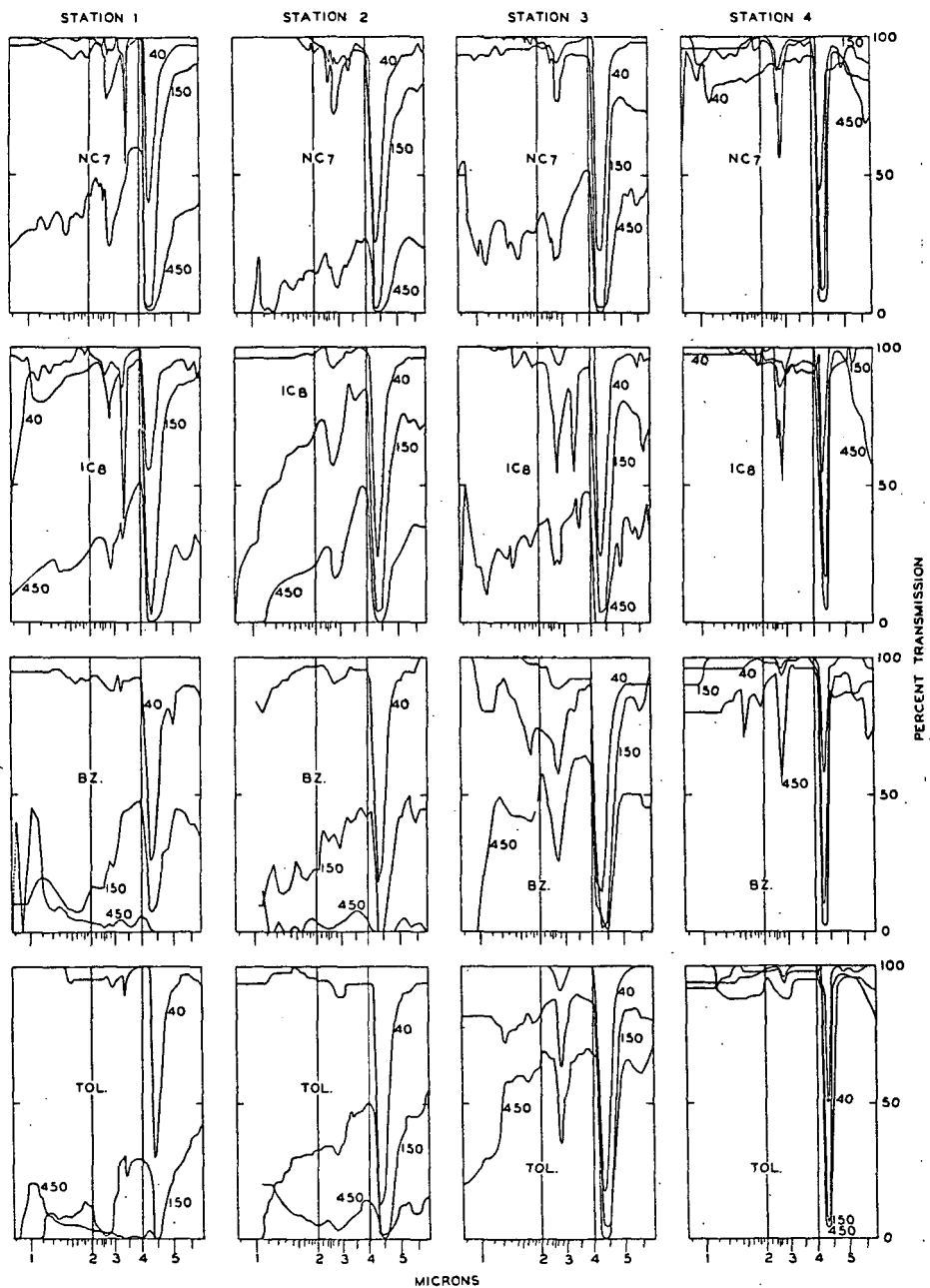


FIGURE 9
FLAME ADSORPTION SPECTRA

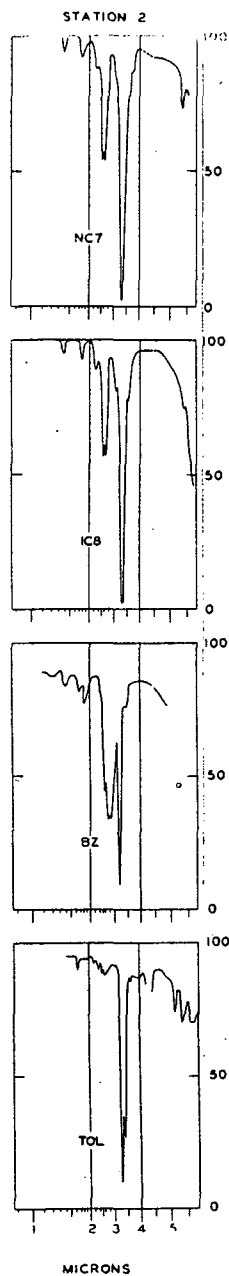


FIGURE 10
ATCIZED FUEL ABSORPTION SPECTRA

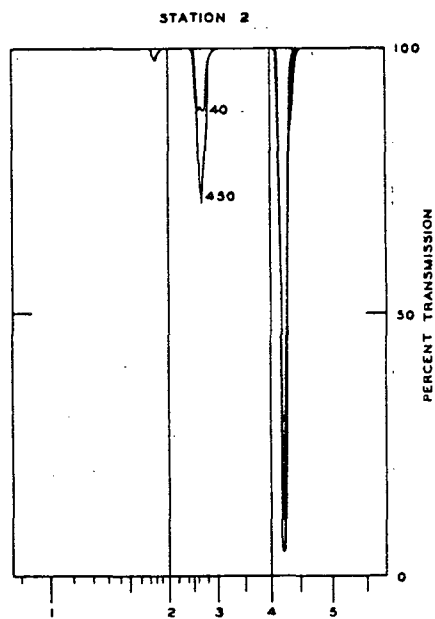
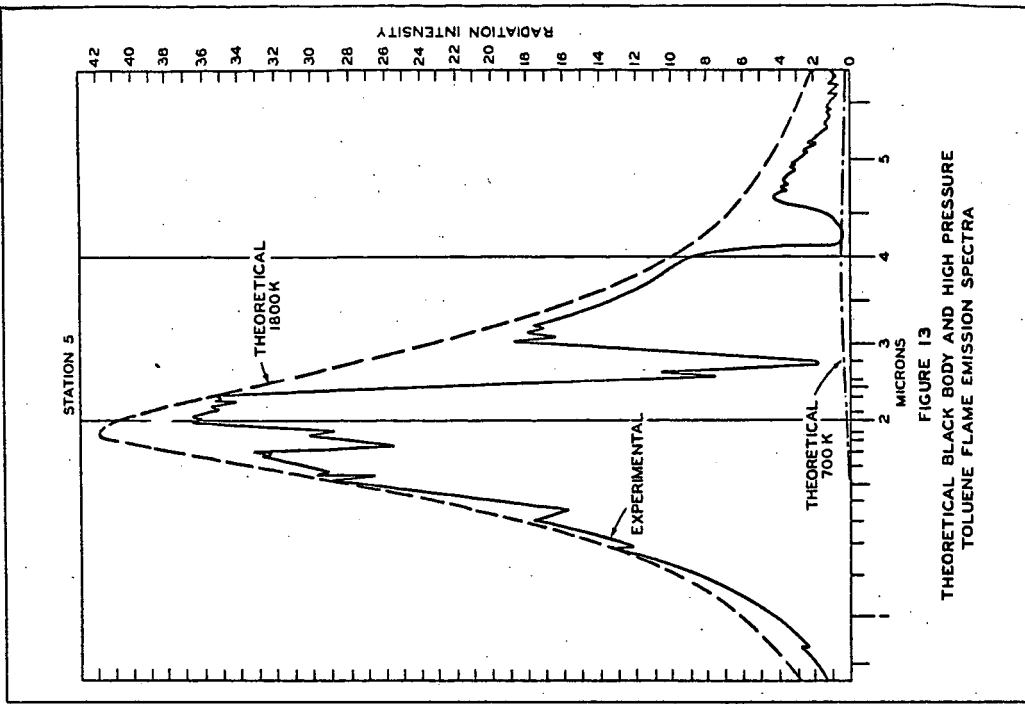
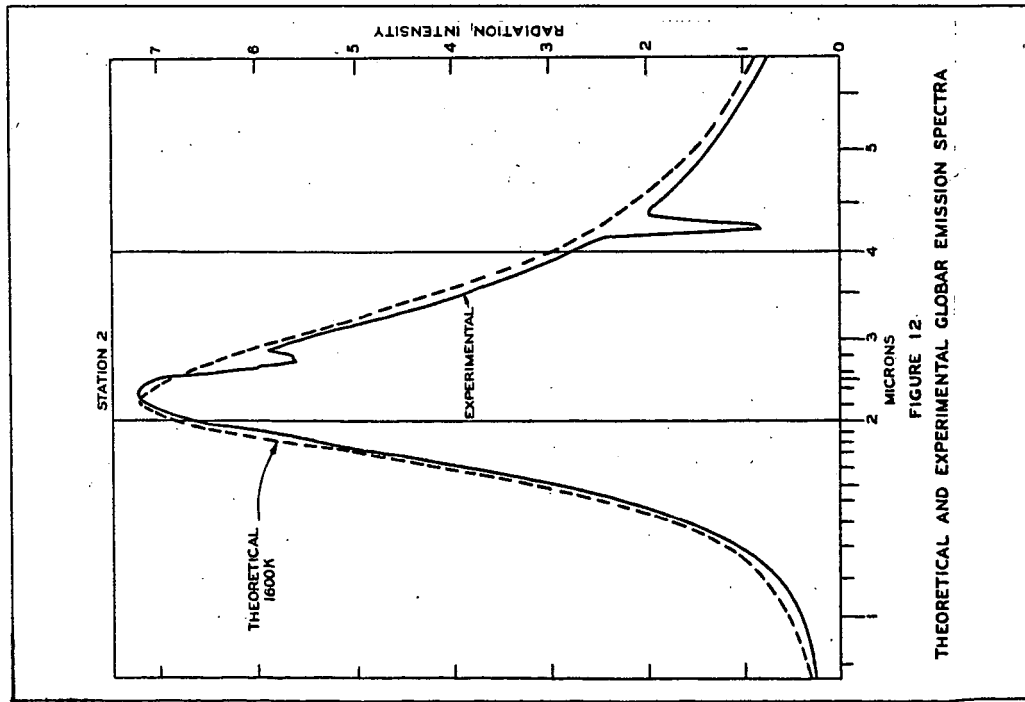
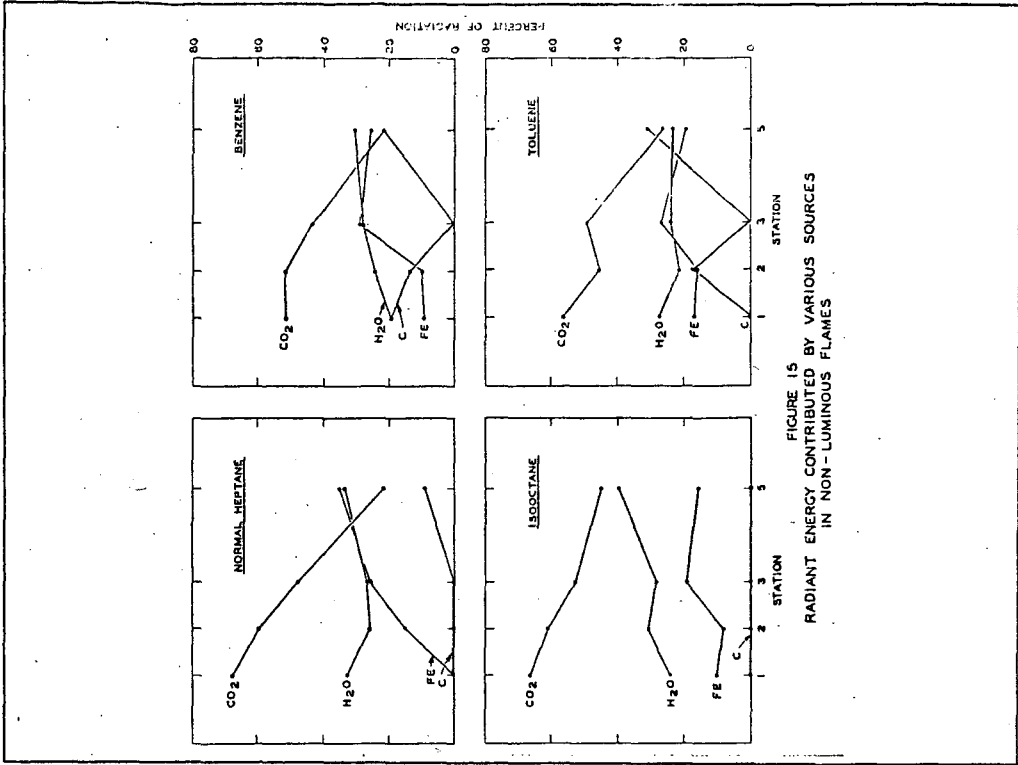
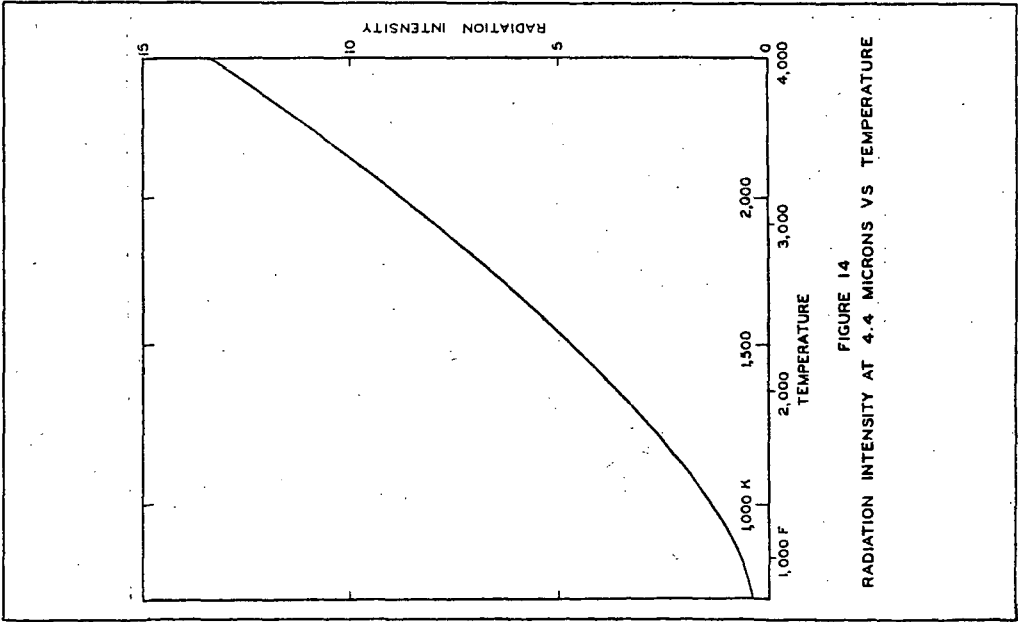
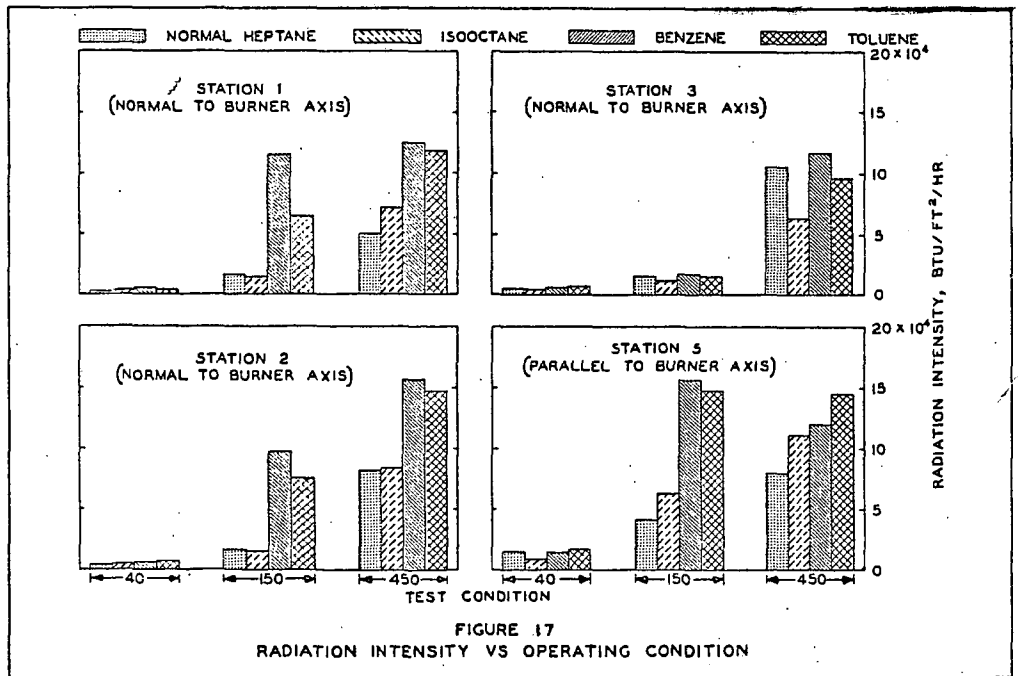
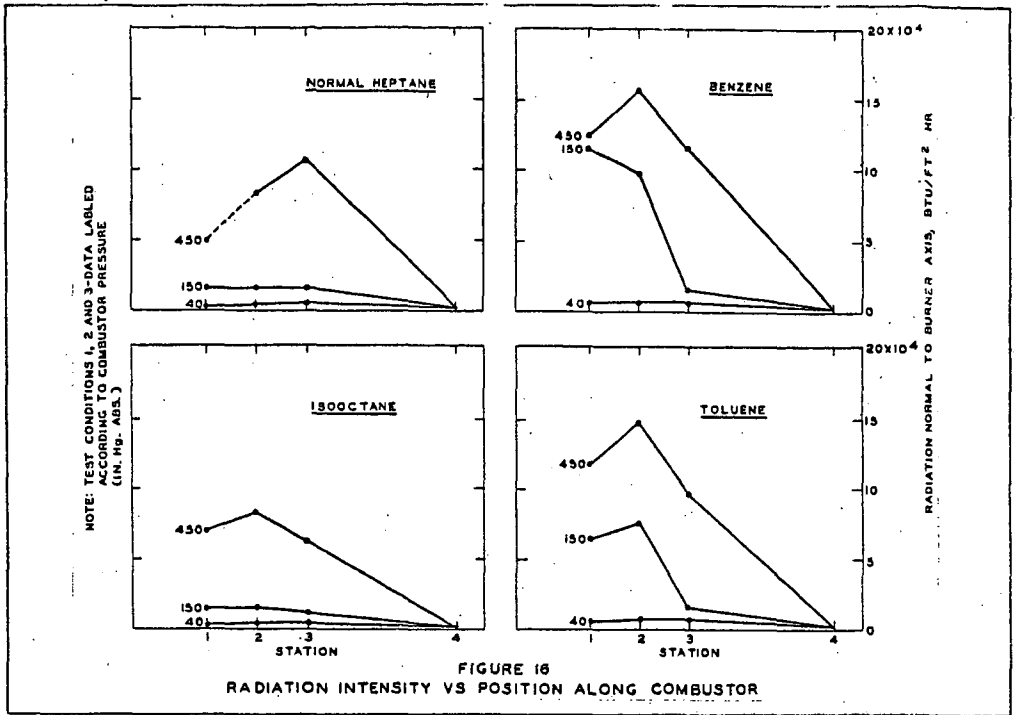


FIGURE 11
AIR PATH ABSORPTION SPECTRA







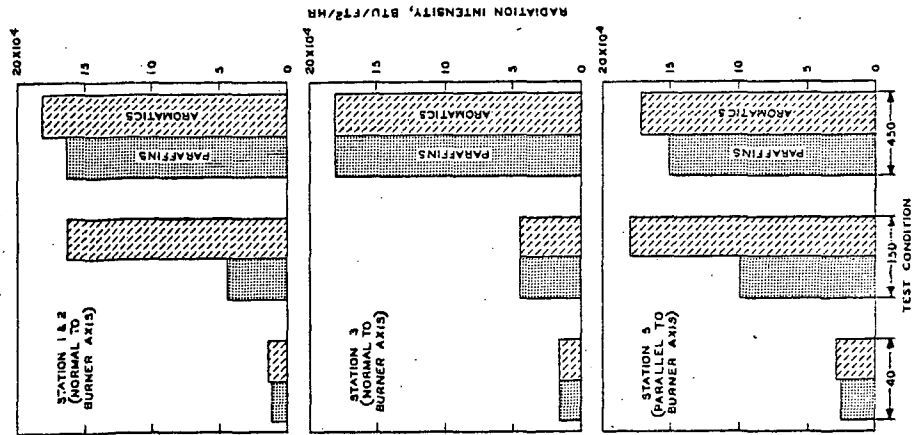


FIGURE 18
RADIATION INTENSITY FOR EXTENDED COMBUSTOR DIMENSIONS

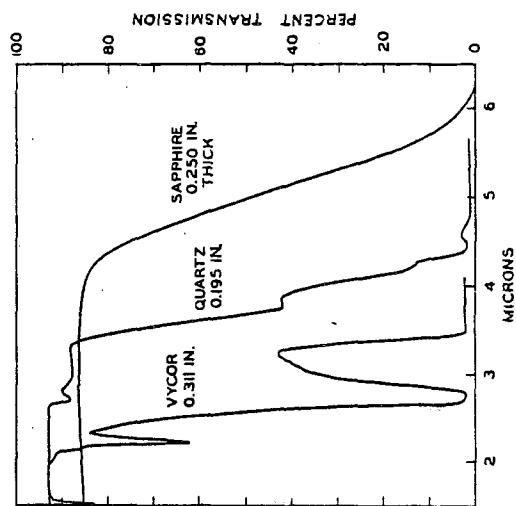


FIGURE 19
TRANSMISSION PROPERTIES OF WINDOW MATERIALS